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Design of a battery management system for PV/Wind system in Lagos, Nigeria

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ABSTRACT

Battery management systems have existed as a technology to monitor the state of charge, voltage, temperature and sometimes state of health of a battery to ensure the battery lifespan is being improved through proper monitoring of this key performance index. This paper focuses on the design of a battery management system for a hybrid renewable energy system comprising wind and PV where battery is the storage system. Different works has been done on battery management system using different methods such as the artificial neural network, coulomb counting method, open circuit voltage method etc. This work uses a hybrid method for state of charge estimation by combining the coulomb counting method and the open circuit voltage method in the state of charge estimation and carries out battery balancing using switched capacitor method. Lead acid battery is the battery used in this case study. The combined method was implemented using bisection formula computation and was proposed to reduce accumulated error in state of charge estimation; as the open circuit voltage method is used once and coulomb counting method used till the battery gets full and when the discharge starts in the next cycle open circuit voltage is used again before coulomb counting. During testing of the prototype, the batteries with an initial voltage of 12.01 and 12.50 were balanced in 45 minutes, to 12.23 volts. The battery management system helps to solve the issue of battery imbalance.

Keywords: Battery management system; Hybrid energy system; Battery pack balancing system; Energy storage systems; Battery balancers.

1. INTRODUCTION

With the need to transition from fossil fuel energy to clean energy systems that relies on renewable means there is need to develop solutions to improve the efficiency of the entire system most especially in terms of energy storage [1] [2]. In terms of improving the efficiency of storage system, there are different considerations that can be made for example; improving the discharge duration [3] of battery (Battery longevity) [4], improving the ease of charging this battery, keeping the batteries at safe thermal operating temperatures, ensuring the batteries are not drained to depth of discharge zone and not overcharged, etc.

Most batteries used in PV/Wind energy systems are faced with the issue of imbalance of cell [5]. This difference or imbalance causes the cell with the most

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charge to be overheated [4] during charging in a pack and also for the battery not to deliver for longer period of time as the weak cell gets drained quicker and prompts the system to reach its cut off voltage [1]. Battery management system ensures that this system can be operated safely and prevent thermal runway of the cell due to overheating [6], [3].

Battery management systems [7] are systems that ensure batteries are operated at safety limits and regions, preventing stress on the battery limits such as over voltage and current. Battery management systems mostly monitors voltage, current and temperature of each battery in its packs, protects the battery from operating outside its safe operating area, monitors its state, computes secondary information such as state of charge (SOC), state of health of the battery and reports it while performing cell balancing to ensure cells contains approximately same amount of charge [8], [9], [10].

As said in literature [5], batteries when kept in a state of imbalance degrades and this decreases its lifespan. The imbalance conditions are caused by different reasons [11] such as differences in the internal resistance of a battery, aging, temperature difference, chemistry of the battery and other factors. In order to solve the issue of battery imbalance [12] it is necessary to develop a battery management system that will estimate the state of charge and balance the SOC in batteries when they are in imbalance condition. This solution is what this research is focused on.

Various approaches [13] have been used in the state of charge estimation, some of which are the artificial neural network method, coulomb counting method, open circuit voltage method, impedance method, kalman filter method, amongst others [14], [15]. The contribution of this research work to already existing knowledge is to combine two methods of coulomb counting and open circuit voltage method using bisection formula for state of charge estimation; switched capacitor active cell balancing for battery SOC balancing method.

Determining the open circuit voltage will be difficult when the batteries are already connected to an inverter system and used to power an AC (alternating current) load. So we determined a relationship [16] between the open circuit voltage and the measured voltage of the battery during loaded conditions. This was used in the algorithm in the micro controller used in building the battery management system circuit. In the future it is possible to use other hybrid methods combination in the bisection formula for state of charge estimation.

2. ESTIMATION

The coulomb counting method for state of charge estimation is one of the most used methods for state of charge estimation. It follows the procedure of using an initial estimate for determining the state of charge for the first initial value and then adding or subtracting the integral of the battery current over time with respect to the battery capacity. The coulomb counting method is reliant on the initial estimate of SOC_O, the precision of the current sensor, accumulative error from integration, temperature, cycle life of battery and battery history.

In the computation of the state of charge based on the coulomb counting method the formula being used is:

$$SOC=SOC_O \pm \int_{T1}^{T2} \frac{Idt}{C} \qquad (1)$$

The positive and negative sign is dependent on if the battery is on charging or discharging conditions.

The open circuit voltage method, if to be used in state of charge estimation needs to consider the relaxation time of the battery before readings of open circuit voltage are being taken. The open circuit voltage is affected by the aging of the battery, the temperature of the battery, environmental conditions at which the battery is being placed, battery chemistry and other factors.

Since we are combining the results from open circuit voltage and coulomb counting we use the bisection formula which operates on determining a particular error value at which the system operates with.

The bisection method operates on the principle of intermediate function. It narrows down the positive and negative interval until it closes in on a correct answer. It is used to find numerical solution with one unknown. It is also known as interval halving method or root finding method.

General Bisection Method Algorithm

We used the below procedure [17] to get the solution for the bisection.

The bisection formula states that for any continuous function f(x),

- Find two points, say a and b such that a < b and f(a)* f(b) < 0

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- Find the midpoint of a and b, say "t"
- t is the root of the given function if f(t) = 0; else follow the next step
- Divide the interval [a, b] by two; If f(t)*f(a) <0, there exist a root between t and a ;else if f(t) *f (b) < 0, there exist a root between t and b
- Repeat above three steps until f(t) = 0.

AREA OF CASE STUDY

Ikoyi Lagos state Nigeria (6° 27.1'N, 3° 24.8'E), is used as a case study location for a hybrid renewable energy system comprising of solar and wind energy systems. Computation on the design of the system using Homergrid software is done based on this location. Lead acid battery is being considered in this research because of its availability and cheap cost.

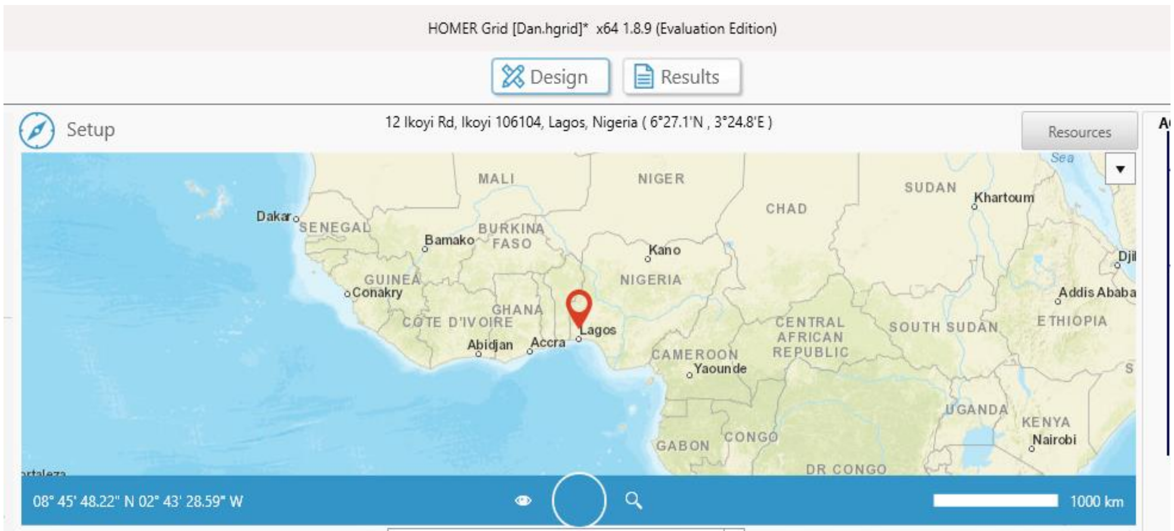


Figure 1: Map location of area of case study by Homergrid software.

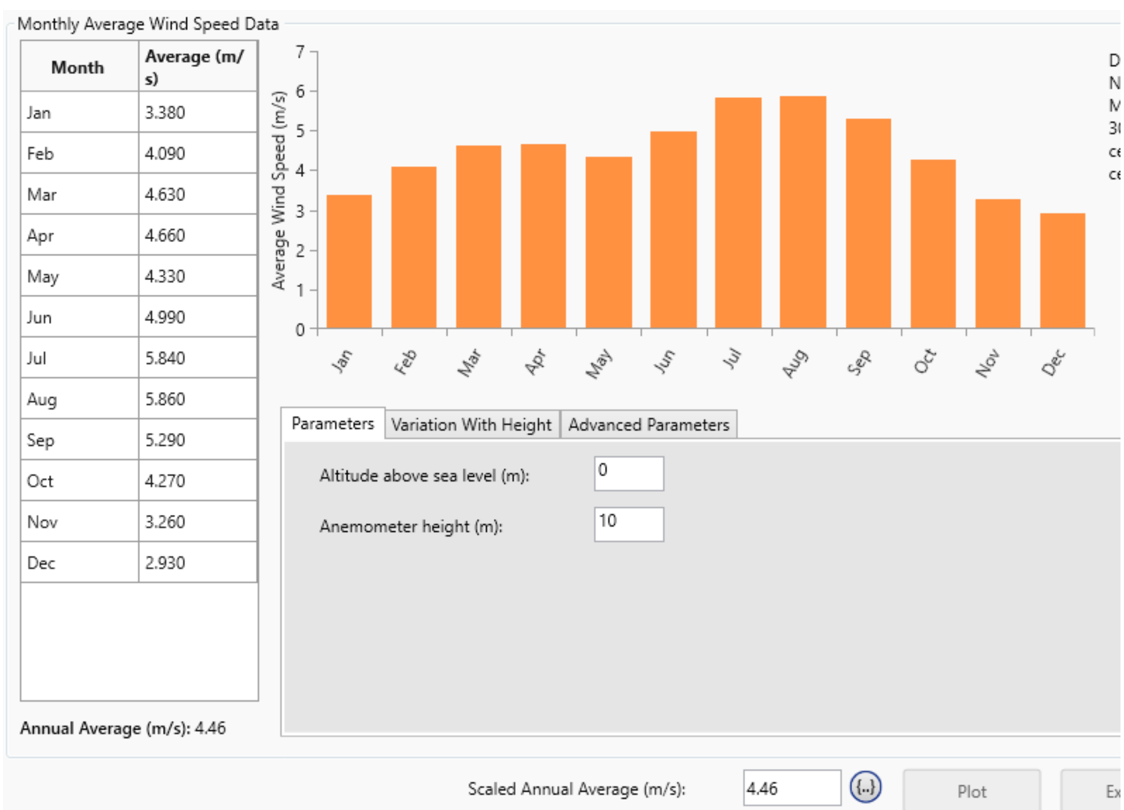
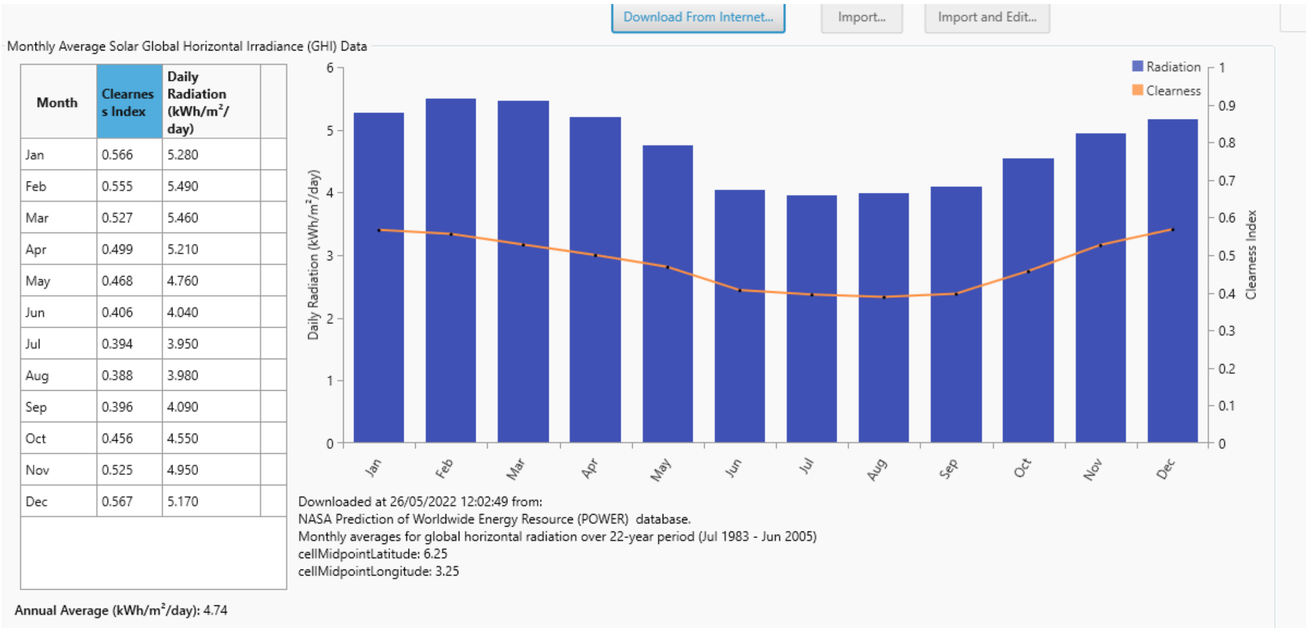
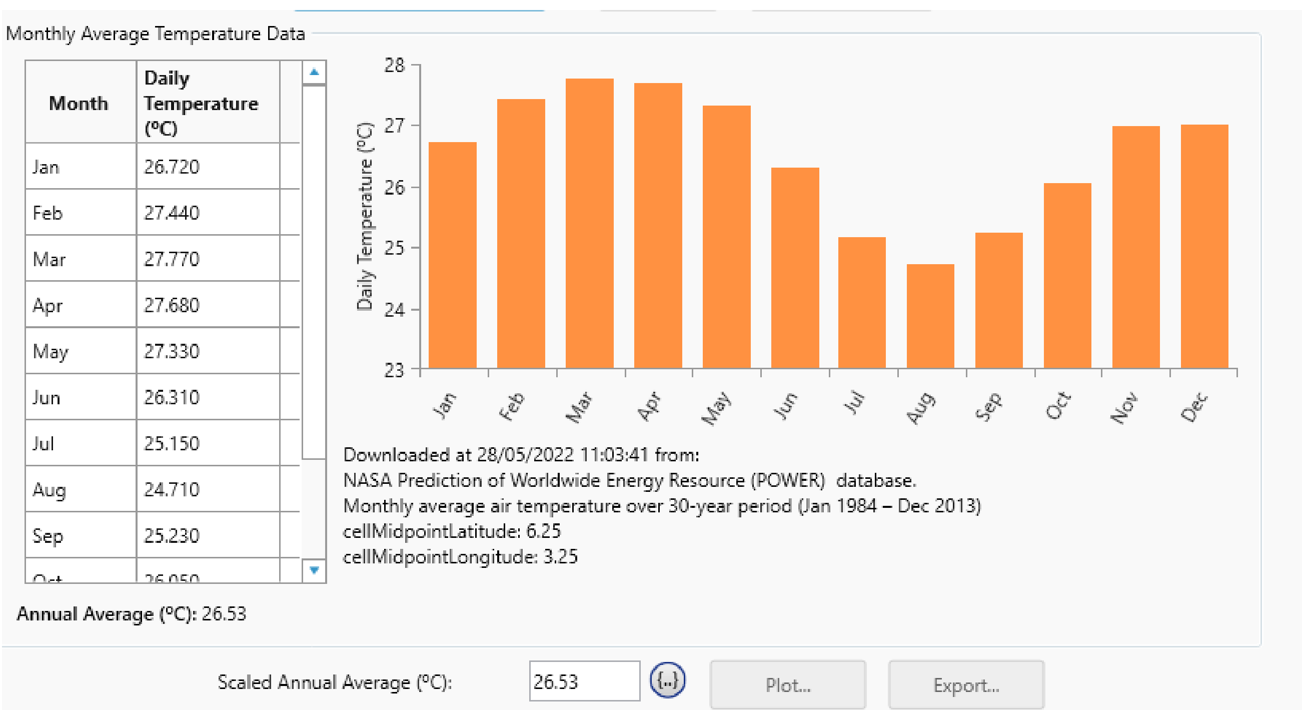


Figure 2. 2022 Monthly average speed of ikoyi lagos from Homergrid Software



Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.566	5.280
Feb	0.555	5.490
Mar	0.527	5.460
Apr	0.499	5.210
May	0.468	4.760
Jun	0.406	4.040
Jul	0.394	3.950
Aug	0.388	3.980
Sep	0.396	4.090
Oct	0.456	4.550
Nov	0.525	4.950
Dec	0.567	5.170

Figure 3. 2022 Monthly average solar Irradiance of Ikoyi Lagos from Homergrid



Month	Daily Temperature (°C)
Jan	26.720
Feb	27.440
Mar	27.770
Apr	27.680
May	27.330
Jun	26.310
Jul	25.150
Aug	24.710
Sep	25.230

Figure 4: 2022 Monthly annual Temperature of Ikoyi as gotten from Homergrid software

From fig. 2 the average annual speed in ikoyi is 4.46 m/s (meter per second) based on results from Homergrid software from NASA while the average annual solar radiation is 197.5w/m² (watt per meter square). In order to design the battery management system, it is necessary to have an idea of the hybrid energy system the device will be used for. We therefore design a hybrid system for a user in Ikoyi, Lagos.

DESIGN OF THE HYBRIB ENERGY SYSTEM

In the design of the battery management system, we found it thoughtful to consider the load and the PV system design to have an idea of where the system is going to be used. So we have made a simple assumption of load analysis in the home of a user in Ikoyi.

Table 1: Night load for the home

Load type	Power demand (W)	Quantity	Total Power (W)
Ceiling Fan	100	3	300
TV	100	2	200
Led Light	30	2	60
		Overall load demand=	**560W**

In this design, we make a consideration of an allowance of 50% of the total load for consideration of a little increment in the load by the user in future. The 50% of 560W (280W) + 560W = 840W. This increment also serves to prevent the overloading of the inverter system.

SIZING THE BATTERY SYSTEM FOR THE PV

Load current to drawn from the battery that will be used in the PV system is: 840/24 =35A.

Since this load can be used in the day and in the night. The PV energy system is designed such that it can sustain the night loads as listed in the table 1.

Assuming this load is to be run for 5 hours (h) then:

35A×5h=175Ah.

For safety of the battery and since the battery considered in this system is lead acid battery; we take into consideration a 50% Depth of Discharge (D.O.D) to increase the safe operating points of the battery and battery health. When we factor the 50% D.O.D we have 175Ah+175Ah=350Ah. In this case we decide to use a 400AH battery bank system.

For the battery bank, we use 12Ah lead acid battery connected in series to get the required battery capacity. We use 12Ah lead acid battery here because it was used in experiment for the battery management device. A practical system will use two 200Ah batteries.

Table 2: Table for day loads in the home

Load Type	Power demand (W)	Quantity	Total power (W)
Water pump	500	1	500

Since the water pump might draw high current then we use allowance of 50% of 500W.

Hence 250W + 500W= 750W.

750/24 = 31.3A.

Hence we need a PV that can provide

(40A + 31.3A)= 71.3 A.

Power requirement for PV= 1711.2W.

Six panels of 300W each will provide the required power for the load and for charging the battery. According to Anderson [18], the formula for computing the maximum power that can be obtained from a PV at a particular place, and given temperature is:

$$\frac{P_{max}\left(\frac{E1}{E2}\right)}{\left(1+\gamma(T1-T2)\right).\left(1+\delta\ln\left(\frac{E1}{E2}\right)\right)} \quad (2)$$

Where:

- Standard solar irradiation at sea level is E2= 1000W/m².
- Standard temperature for optimum solar performance T1=25°c and the values [18] for the constants are given in the table 3:

Table 3: Table for coefficient constants for monocrystalline panel as gotten from Homergrid software

EQUATION PARAMETERS	VALUE FOR MONOCRYSTALLINE PANEL
$\alpha(^{o}C^{-1})$	0.0095
$\beta\ (^{o}C^{-1})$	-0.0031
$\Upsilon(^{o}C^{-1})$	-0.0033
δ	0.085

Equation (2) can be used to calculate the maximum power of a monocrystalline PV at a particular time, temperature and other conditions being known [18]. For the design of the hybrid energy system comprising the solar and wind, we used Homergrid software to show the interconnection and design as shown in figure 5.

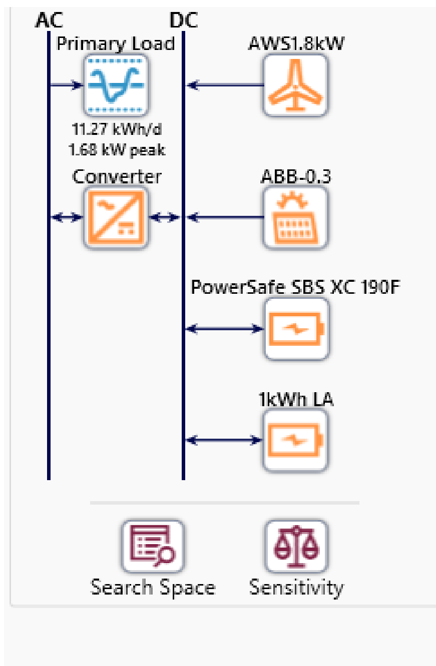


Figure 5. Homergrid software design showing interconnection of the hybrid energy system

We choose AWS 1.8KW wind turbine. The wind turbine has the following description:

Table 4: Technical specification of Wind turbine used

MODEL	AWS-HC 1.8KW
RATED WIND SPEED m/s /mph	10.5/24
PEAK OUTPUT	2200W
POLES	16
RPM-50hz/60hz	375/450
ROTOR DIAMETER	3.4m
NUMBER OF BLADES	3
SWEPT AREA	9.4 Sq. m
TIP SPEED RATIO	8.5
MINIMUM TIP CLEARANCE cm	20/11

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SYSTEM DESIGN OF THE BATTERY MANAGEMENT CONTROLLER

The complete system for the hybrid renewable energy is made of the solar and wind energy system with lead acid battery for energy storage, a charge controller and BMS.

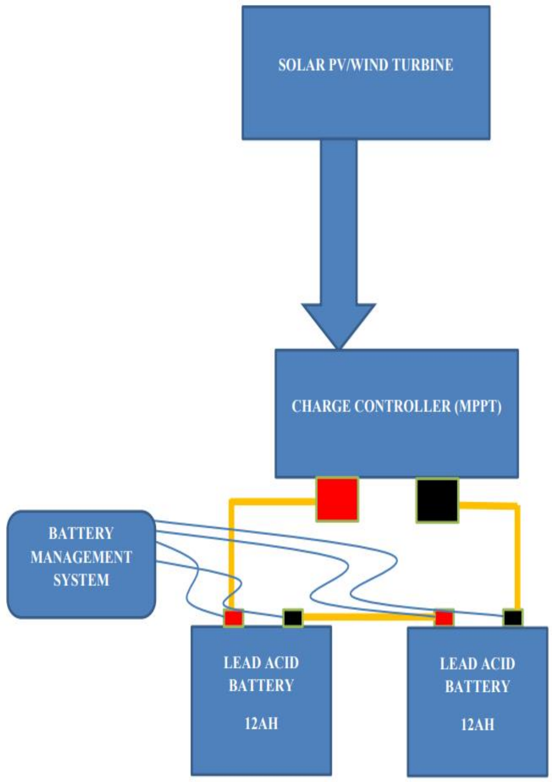

Figure 6. Block diagram of the system

The diagram (fig 6) shows how a hybrid system will be connected with a battery management system. The battery management system is to be connected to the batteries to perform the level of charge monitoring and balancing (in the situation where there is imbalance).

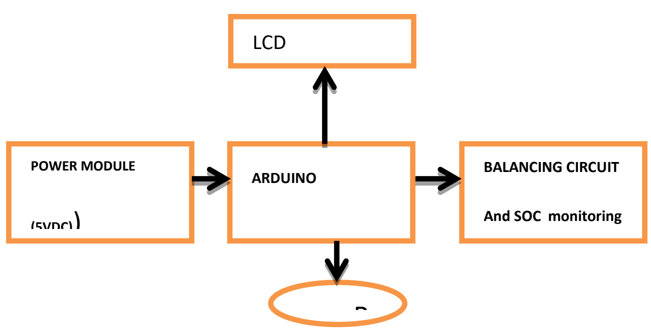

Figure 7. Block Diagram of the battery management system

The system comprises the hardware and the software which works in synchronism to achieve the control and monitoring operation. For the hardware part, the sensors read data of temperature, voltage, and current of the battery and send it to the arduino micro-controller. The data result tells the arduino at what time to give instruction to the mosfet to switch between charging and discharging a capacitor through switched capacitor active cell balancing methodology. The circuitry of the battery management system comprise the LCD, power input section, balancing circuit section and the sensor measurement section as shown in fig. 7.

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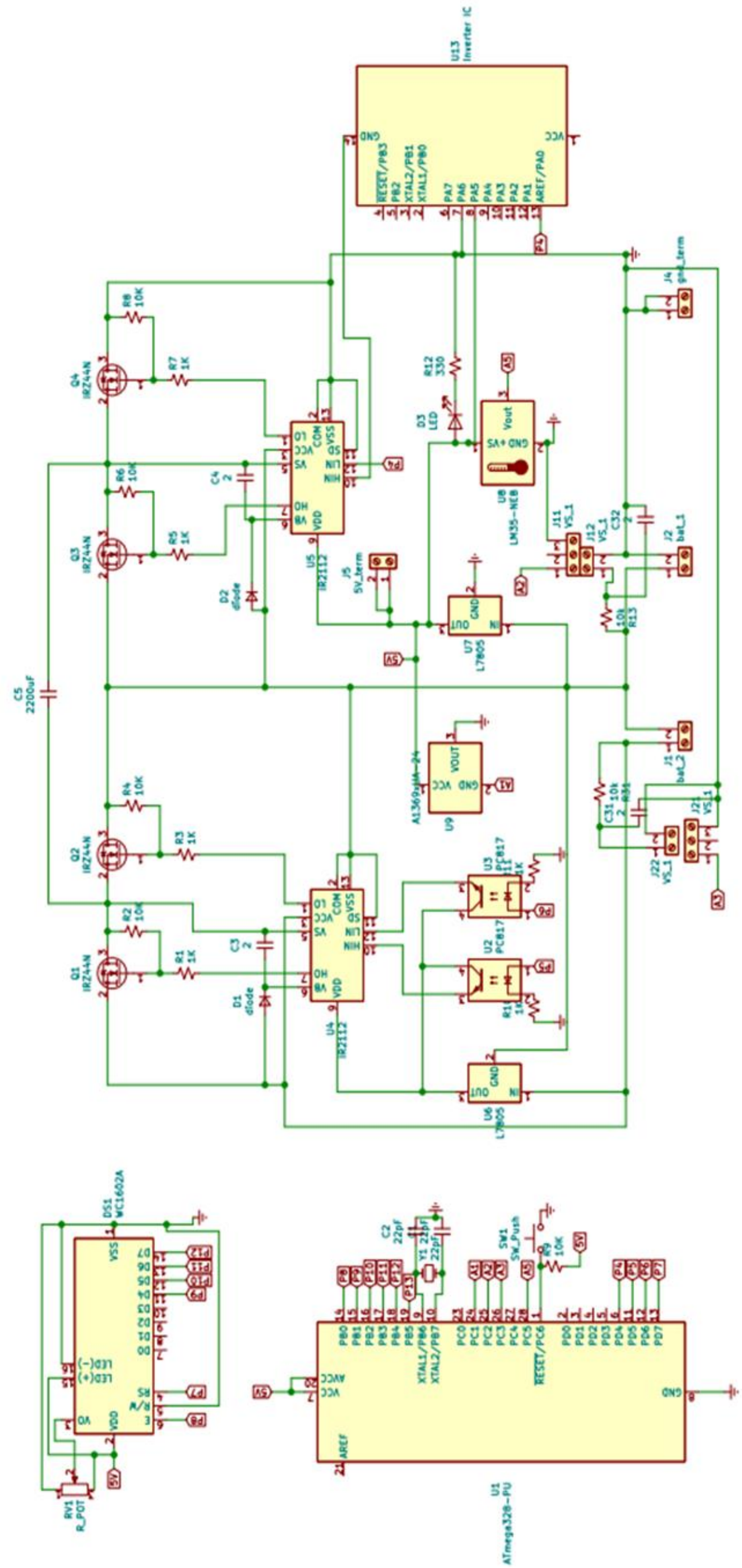

Figure 8. Proteus design of the circuit of the battery management system

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OUTLINE OF THE ROLES THE BATTERY MANAGEMENT SYSTEM SHALL PERFORM

- Real time estimation of the state of charge of the battery using combined method of open circuit voltage and coulomb counting.
- State of charge balancing of battery
- Display of the battery KPI such as the voltage, current and temperature.
- Display of the time it takes for active balancing.

The circuit comprise the charging section, which provides charge to the battery through wind and solar hybrid energy system, the arduino for the controller and the balancing circuit. Switched capacitor active cell balancing method was used transferring charge from the battery with higher state of charge to the other with lesser state of charge. This was achieved using Mosfet.

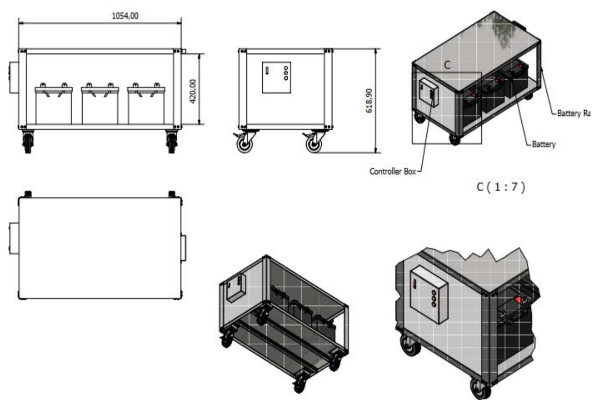

Figure 9. Autocad drawing of the controller of the battery and the battery rack.

The battery management system is to be used in a real time system as shown in fig 7. The diagram explains how it is to be used in a real time. The drawing above shows the battery rack and the battery controller box where the circuitry will be contained. The controller box is 0.6ft × 0.6ft in dimension.

ALGORITHM FOR THE PROGRAM CODE FOR BMS

- Start
- //voltage=Current=C, temperature=T
- Read T, C, T
- $SOC_{opencircuit}= V_{measured} \pm K_V$
- //K_V is the correction factor
- SOCcouloumbcounting=
- $SOC_{opencircuit} \pm \int_{T1}^{T2} Idt/C$
- Perform bisection method based on two results gotten from the open circuit voltage and the coulomb counting method.
- If SOC1>SOC2 or SOC2>SOC1
- Balance SOC;
- Print balancing SOC;
- Else;
- Print battery SOC BALANCED
- End.

3. RESULTS

In carrying out the open circuit voltage reading, since the voltage of the battery to be measured will be the voltage when the battery is connected to the load it is necessary to carry out an experiment to determine a correction parameter that will be used in relating the open circuit voltage without load and the voltage without load. To determine a correction parameter that will relate between the battery voltage on load and voltage without load, a correction parameter correction factor is being determined.

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In order to carry out this experiment, we have decided to carry out a discharge test on a 12Ah lead acid battery and record the voltage on load and voltage without load. The procedure for carrying the experiment is thus:

1. We measure the voltage of a charge 12Ah battery and record it
2. We connect a 24watt DC load and record the voltage on load and voltage after disconnecting the load
3. We record the open circuit voltage using a rest time of 10 minutes.

The following data were gotten:

Table 5. Table of values for experiment on correction factor

Discharge time (mins)	V_{BD} 0 min **(Volts)**	V_{OD} 30 mins **(Volts)**	V_{AD1} **(Volts)**	V_{AD2} **(Volts)**
30	13.20	12.50	12.74	12.80
30	12.80	12.44	12.61	12.72
30	12.72	12.37	12.54	12.63
30	12.63	12.30	12.47	12.54
30	12.54	12.21	12.37	12.45
30	12.45	12.11	12.30	12.35
30	12.35	12.00	12.19	12.21
30	12.21	11.87	12.00	12.10
30	12.10	11.76	11.93	11.99
30	11.99	11.66	11.84	11.94
30	11.94	11.53	11.20	11.80
30	11.80	11.26	11.42	11.64
30	11.64	10.72	10.95	11.46

Where:

- **V_{BD}** is Voltage of battery before discharge.
- **V_{OD}** is Voltage of battery on discharge 30 minutes after the load are connected.
- **V_{AD}** is Voltage after discharge but before the battery is allowed to rest
- **V_{AD2}** is Voltage after discharge after 10 minutes rest time.

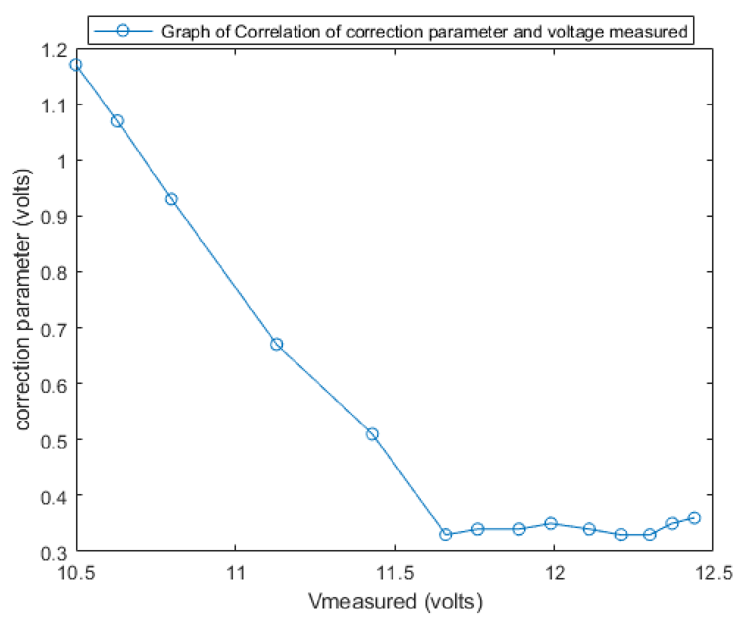

Figure 10. Line plot of correction factor and measured voltage for the lead acid battery.

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From the graph gotten (fig 10 and fig 11) we computed the gradient and equation, using line of best fit for the region between 10.5 and 11.66; while we found the mean for the values of $V_M \geq 11.66$. This gave two linearization's which are:

$$K_V = \begin{cases} -0.21Vm + 1.562 & \textit{Others} \\ 0.342 & \text{for } Vm \geq 11.66 \end{cases}$$

V_M is the measured voltage and V_{oc} is the open circuit voltage after resting.

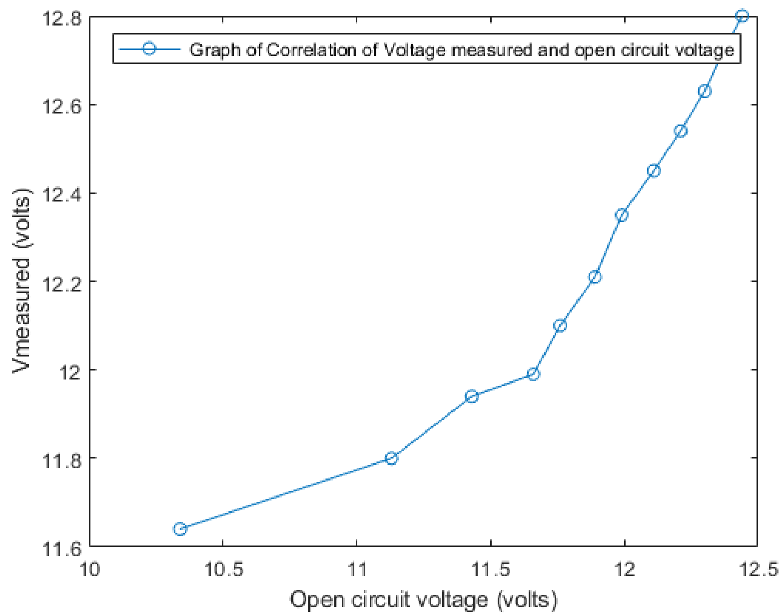

Figure 11. Correlation of open circuit voltage and measured voltage of the 12Ah lead acid battery.

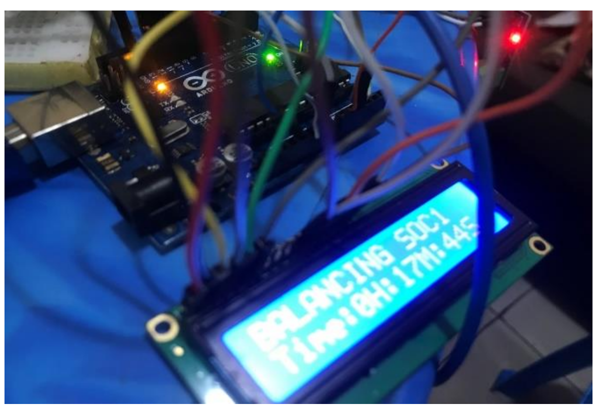

Figure 12. Photo taken after implementing and testing the circuit on a bread board for testing.

The experiment showed that the state of charge of the battery was being balanced and the time for balancing was 45 minutes.

4. CONCLUSION

Battery management system helps to monitor the state of charge and state of health of batteries. The battery management system designed in this work made use of switch capacitor balancing method using hybrid method of coulomb counting and open circuit voltage method for state of charge estimation. Bisection method was used in combining the results of state of charge estimation gotten from open circuit voltage method and coulomb counting method. The programming of the micro-controller was done using C++ programming language. For the result of SOC for open circuit voltage method, since the battery is assumed to be used

continuously, a correction factor K_V, which shows the relationship between the battery on load and without load was estimated. For V_M, measured voltage ≤ 11.65, V_M has a value of $-0.21V_M+1.562$ and 0.342 for others. This correction factor was gotten by performing a discharge test on a 12Ah (Long WP12-12A) lead acid battery and allowing a resting time of 10mins before taking readings of the open circuit voltage. 24 watts was used as the load for the discharge test for estimating the correction factor. We used a 220μF capacitor with a switching time of 0.4 milliseconds for balancing. The mosfet used here had a low resistance of 28 milli ohms with Vgs not more than 20volts.

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Conflicts of interests

The authors declare that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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